Vernier learning with short- and long-staircase training and its transfer to a new location with double training

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We previously demonstrated that perceptual learning of Vernier discrimination, when paired with orientation learning at the same retinal location, can transfer completely to untrained locations (Wang, Zhang, Klein, Levi, & Yu, 2014; Zhang, Wang, Klein, Levi, & Yu, 2011). However, Hung and Seitz (2014) reported that the transfer is possible only when Vernier is trained with short staircases, but not with very long staircases. Here we ran two experiments to examine Hung and Seitz's conclusions. The first experiment confirmed the transfer effects with short-staircase Vernier training in both our study and Hung and Seitz's. The second experiment revealed that long-staircase training only produced very fast learning at the beginning of the pretraining session, but with no further learning afterward. Moreover, the learning and transfer effects differed insignificantly with a small effect size, making it difficult to support Hung and Seitz's claim that learning with long-staircase training cannot transfer to an untrained retinal location.

Introduction

Perceptual learning leads to long-term improvements of discrimination of basic visual features, such as contrast, orientation, direction, and Vernier alignment. One hallmark of perceptual learning is the frequent observations that learning is specific to the orientation and retinal location of the trained stimulus (Dosher & Lu, 1998; Poggio, Fahle, & Edelman, 1992; Schoups, Vogels, & Orban, 1995). Such learning specificity has inspired theories that interpret visual perceptual learning as a result of training-induced neural plasticity in the early visual areas (Bejjanki, Beck, Lu, & Pouget, 2011; Karni & Sagi, 1991; Schoups et al., 1995; Teich & Qian, 2003) or improved readout through response reweighting (Dosher & Lu, 1998; Law & Gold, 2009; Poggio et al., 1992; Yu, Klein, & Levi, 2004).

However, when learning fails to transfer to a new orientation or location, it does not necessarily mean that learning is really orientation or location specific. The new orientation or location is neither bottom-up stimulated nor top-down attended during training, which could prevent learning from functionally connecting to the new orientation or location for learning transfer (Xiong, Zhang, & Yu, 2016). In a series of double-training studies, we demonstrated that when training is paired with the observers' additional exposure of the new orientation or location via an irrelevant task, learning becomes significantly and often completely transferable (Wang, Cong, & Yu, 2013; Wang, Zhang, Klein, Levi, & Yu, 2012; Wang et al., 2014; Xiao et al., 2008; Zhang & Yang, 2014; Zhang et al., 2010).

Among these double-training findings, the most extreme case is the "piggybacking" effect whose mechanism is still under investigation (Wang et al., 2014; Zhang et al., 2011). We observed that peripheral Vernier learning in one retinal quadrant, which is highly location specific, can be piggybacked to other untrained retinal quadrants when Vernier training is paired with orientation-discrimination training at the same location. This surprising effect has been replicated by Hung and Seitz (2014), but with an exception. They reported that when Vernier training is performed with a single long staircase (~800 trials) in each training session, instead of multiple short staircases (10 reversals and approximately 50~60 trials each) as in Wang et al. (2014), Vernier learning fails to transfer to untrained locations. This exception, if verifiable, would provide important constraints on the effectiveness of double training, as well as useful insights into the perceptual

C : , J.-., & , C. (2018). . *Journal of Vision*, *18*(13):8, 1 8, :// /10.1167/18.13.8.

https://d i. rg/10.1167/18.13.8 Received March 14, 2018; published December 14, 2018 ISSN 1534-7362 C pyright 2018 The Auth rs

learning mechanisms. We decided to replicate both the short- and long-staircase experiments to check Hung and Seitz's conclusions.

Methods

Observers

Eighteen inexperienced and naïve observers (mean ± $D = 21.6 \pm 2.0$ years) with normal or corrected-to-normal vision participated in the experiments. Informed written consents were obtained before the experiments. The experiments adhere to the Declaration of Helsinki.

Apparatus

The setup was identical to that in Wang et al. (2014). The stimuli were generated with Psychtoolbox-3 software (Pelli, 1997) and presented on a 21-in. CRT monitor—for Vernier stimuli: 2,048 pixel × 1,536 pixel, 0.19 mm (H) × 0.19 mm (V) per pixel, 75 Hz frame rate; for orientation stimuli: 1,024 pixel × 768 pixel, 0.38 mm (H) × 0.38 mm (V) per pixel, 120 Hz frame rate. The mean luminance was 50 cd/m^2. The luminance of the monitors was linearized by an 8-bit look-up table. Viewing was monocular with one eye covered with a translucent plastic pad, and a chin-and-head rest helped stabilize the head of the observer. Experiments were run in a dimly lit room. The viewing distance was 1 m.

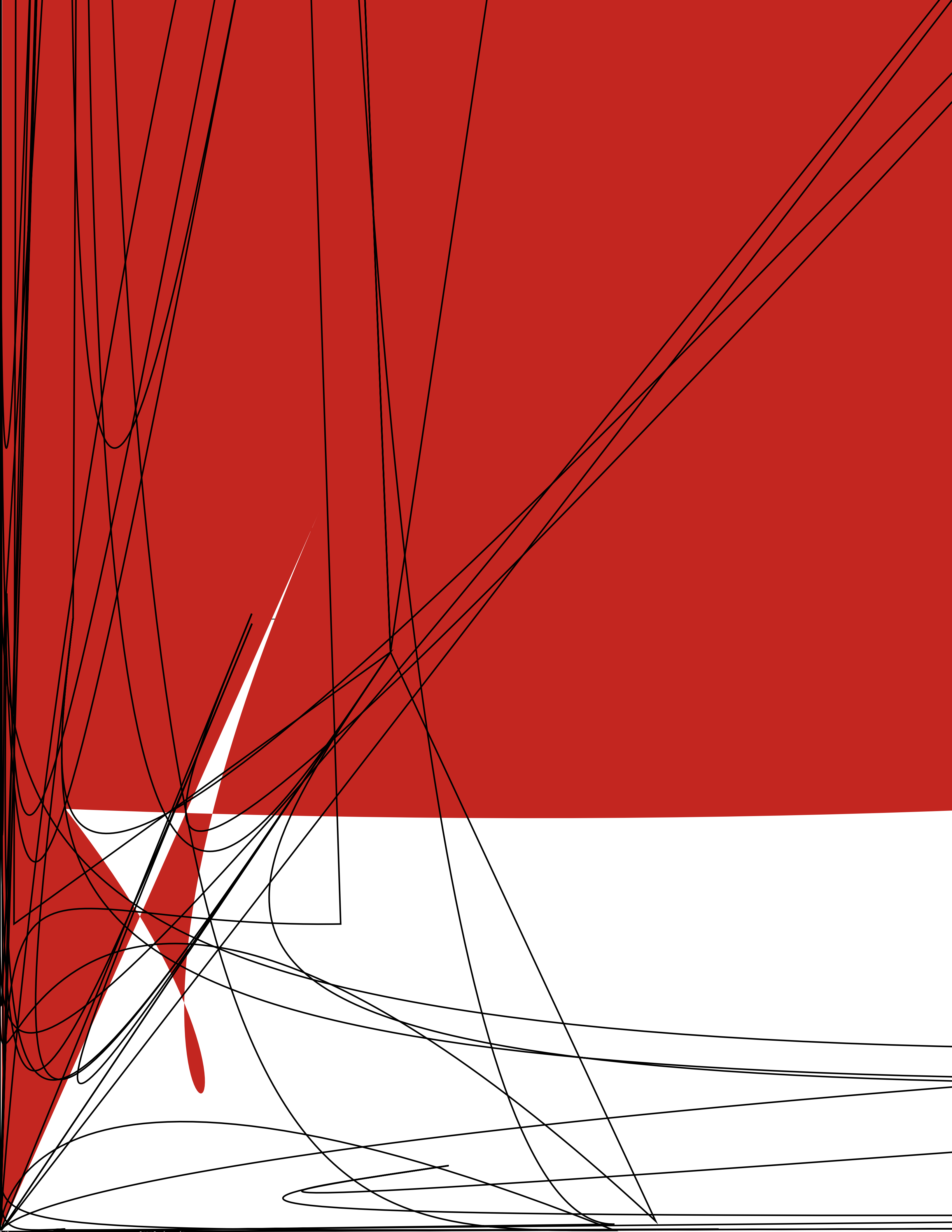
Stimuli

The Vernier and orientation stimuli (Figure 1a) were also identical to those used in Wang et al. (2014). The Vernier stimulus consisted of a pair of identical Gabors presented at 5° retinal eccentricity (spatial frequency = 3 c/°, $D = 0.29°$, contrast = 0.47, orientation = vertical or horizontal, and center-to-center distance = 4λ). The orientation stimulus was a Gabor also presented at 5° eccentricity (spatial frequency = 1.5 c/°, $D = 0.29°$, orientation = 36° or 126°, contrast = 0.47, and phase randomized for every presentation). Stimuli were viewed through a circular opening of a black cardboard.

Procedure

Vernier thresholds were measured with a single-interval staircase procedure. In each trial, the stimulus was presented for 200 ms. The observers judged whether the lower Gabor was to the left or right of the upper Gabor. A small foveal fixation cross preceded each trial by 500 ms and stayed through the trial.

Orientation discrimination thresholds were measured with a temporal two-alternative forced-choice staircase procedure. In each trial, the reference and test orientations were separately presented in the two 100-ms stimulus intervals in a random order with a 500-ms interstimulus interval. The observers judged which stimulus was more clockwise. A small fixation point preceded each trial by 400 ms and stayed through the



20 trials to familiarize themselves with the training task before the pretraining phase.

In the training phase of the short-staircase training experiment, each observer practiced eight short staircases of Vernier discrimination and eight short staircases of orientation discrimination at the same location in an interleaved manner in each of five daily sessions. In the training phase of the long-staircase training, each observer practiced one long staircase of Vernier discrimination and eight short staircases of orientation discrimination at the same location. The eight segments of the long staircase and eight short staircases were interleaved in each of five daily sessions. The duration of each session lasted for 1.5–2 hrs, including rest times between staircases or segments.

Eye movement control

We used an Eyelink II eye tracker (SR Research, Kanata, Ontario, Canada) to monitor eye movements. The eye tracker allowed new trials to start only when observers fixated at the center of the screen (within a 2° radius fixation window). If an eye movement outside of this window was detected at any moment during a trial, this trial was aborted (and excluded from data analysis). These aborted trials accounted for 5.4% of total trials. In addition, we analyzed the remaining trials in pretraining and posttraining sessions in all eight observers in Experiment 1 (Figure 1; Experiment 2 also used the same pretraining and posttraining conditions). It turned out that in 94.4% ± 3.6% (*D*) of the trials the eye positions were at least 4° away from the target. Therefore, the accuracy of our results was not much affected by improper eye movements.

Results

Experiment 1: Vernier learning through short-staircase training and its transfer with double training

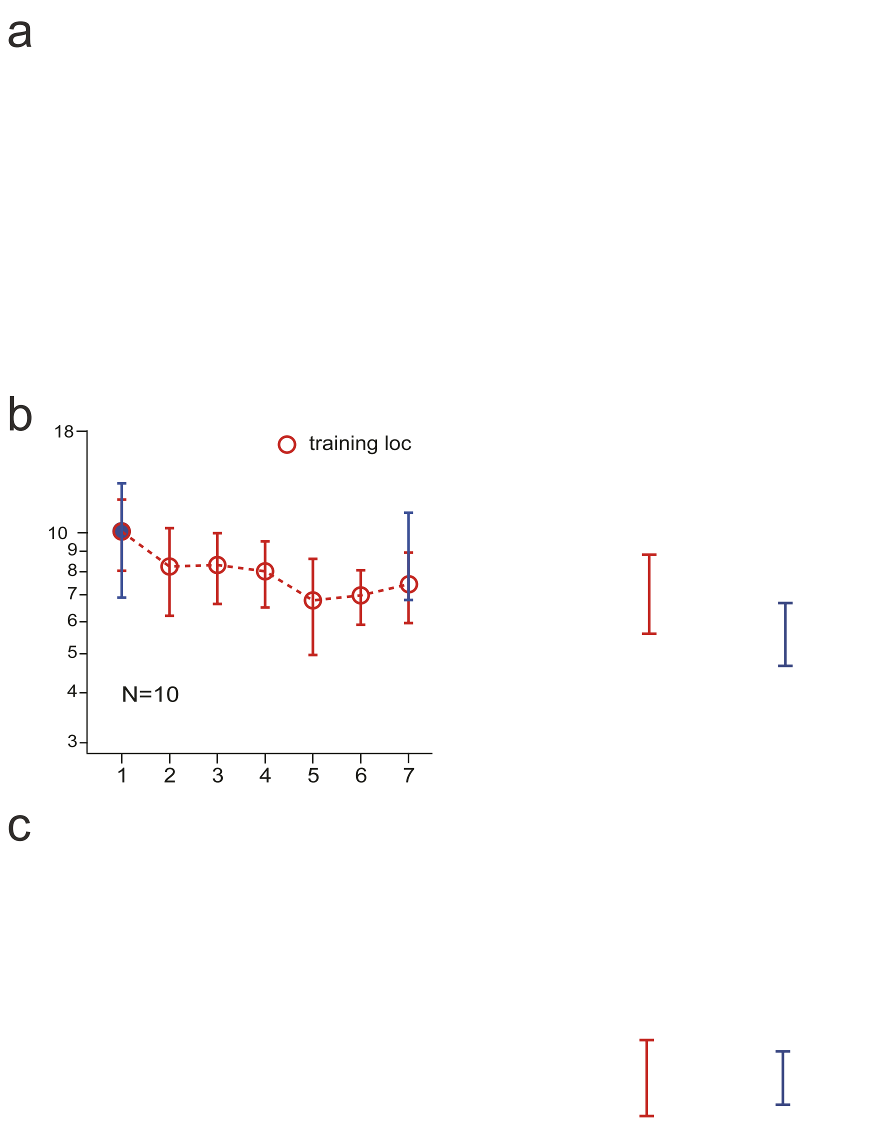
Short-staircase Vernier training, along with orientation training at the same location (Figure 1a), improved Vernier thresholds at both the training and transfer locations as shown by staircase-by-staircase changes of Vernier thresholds at the training and transfer locations in Figure 1b. The Vernier thresholds showed a fast decline from the first to second staircases (at both locations). After that, the thresholds declined gradually over the whole training course as indicated by the loglinear fit (Figure 1b). The mean slope of the fit line was –0.049, 95% confidence interval (CI) [–0.075, –0.023], which was significantly different from zero, (7) = −4.466, = 0.003, Cohen's = −1.58, indicating substantial learning.

We used the percentage improvement, (1 − posttraining threshold/pretraining threshold) × 100, to indicate the learning and transfer effects. When the pretraining and posttraining thresholds were the first-staircase thresholds at in Hung and Seitz (2014; Figure 1c), the Vernier performance improved by 36.31%, 95% CI [5.78%, 66.85%], at the training location and by 35.83%, 95% CI [9.71%, 61.94%], at the transfer location (Figure 1c, right). A repeated-measures ANOVA indicated a significant main effect of training, $F(1, 7) = 10.58$, $= 0.014$, $\eta^2 = 0.602$, but an insignificant main effect of location, $F(1, 7) = 0.003$, $= 0.96$, $\eta^2 < 0.001$. When the geometric means of thresholds over all five to six staircases in the pretraining and posttraining sessions were used as pretraining and posttraining thresholds (Figure 1d), as in our previous studies, the Vernier performance improved by 27.43%, 95% CI [14.58%, 40.28%], at the training location and by 20.86%, 95% CI [5.80%, 35.92%], at the transfer location. A repeated-measures ANOVA indicated a significant main effect of training, $F(1, 7) = 17.65$, $= 0.004$, $\eta^2 = 0.716$, but an insignificant main effect of location, $F(1, 7) = 5.36$, $= 0.054$, $\eta^2 = 0.433$.

These results were largely consistent with Wang et al. (2014) and Hung and Seitz (2014) that Vernier learning with short-staircase training can transfer substantially and sometimes completely to a diagonal location with double training. However, the effect sizes of the training and location effects revealed by ANOVA were smaller when the measurements were based on the first-staircase thresholds than on geometric means of all five to six staircases. This is because the improvements at both training and transfer locations and the differences between the training and transfer locations all had larger individual differences when first-staircase thresholds were used (Figure 1c vs. 1d, right panels).

Experiment 2: Vernier learning through long-staircase training and its transfer with double training

The mean Vernier learning curve with long-staircase training was very different from the one with short-staircase training (Figure 2a). Vernier learning occurred mainly from the first to the second staircases in the pretraining session. After this very fast learning, there was no further improvement throughout the training course. These results were similar to Hung and Seitz (2014), in which most learning also occurred from the



was insignificantly different from zero, (9) = −2.01, = 0.075, Cohen's = −0.64, but significantly different from the slope of learning curves with short-staircase training, t(16) = 2.65, = 0.009, Cohen's = 1.40, two-tailed unpaired test.

When the first-staircase thresholds were used, double training with long-staircase Vernier training improved the Vernier thresholds by 22.95%, 95% CI [7.64%, 38.25%], at the training location and by 6.65%, 95% CI [–5.52%, 18.83%], at the transfer location (Figure 2b).

The mean learning and transfer effects appeared similar to Hung and Seitz's (2014) report that most learning did not transfer. However, a repeated-measures ANOVA indicated a significant main effect of training, $F(1, 9) = 14.48$, $= 0.004$, $\eta^2 = 0.617$, but an insignificant main effect of location, $F(1, 9) = 2.98$, $= 0.118$, $\eta^2 = 0.249$, because of the large variations of the improvement differences between training and transfer locations (Figure 2b, right). Here the value ($= 0.118$) may not be a good indicator of the location effect because of the relatively small sample size ($= 10$; $= 6$ in Hung & Seitz). However, the effect size ($\eta^2 = 0.249$), which is a more informative indicator and is in principle independent of the sample size (Cumming, 2014), is also small. These results, thus, indicate that Vernier learning with long-staircase training was limited to fast learning at the very beginning of training. Moreover, the small effect size of the location main effect makes it difficult to support Hung and Seitz's claim that Vernier learning with long-staircase training cannot transfer to an untrained location. In addition, when the pretraining and posttraining thresholds were the geometric means over all staircases in the corresponding pretraining and posttraining sessions, Vernier thresholds were virtually unchanged by −2.21%, 95% CI [−17.58%, 13.16%], at the training location and by −2.23%, 95% CI [−13.04%, −8.58%], at the transfer location. A repeated-measures ANOVA indicated insignificant main effects of training, $F(1, 9) = 0.223$, $= 0.648$, $\eta^2 = 0.024$, and location, $F(1, 9) < 0.000$, $= 0.997$, $\eta^2 < 0.001$.

Discussion

Our short-staircase training results confirm the previous reports that Vernier learning, when paired with orientation training at the same retinal location, can transfer to a diagonal location (Hung & Seitz, 2014; Wang et al., 2014; Zhang et al., 2011). The long-staircase training results suggest only fast learning at the very beginning of training (from first to second staircases) with no further learning afterward, which is different from learning with short-staircase training that progresses over the entire training course. Moreover, ANOVA analysis reveals not only insignificant difference between performance improvements at training and transfer locations, but also a small effect size. Therefore, our results do not support Hung and Seitz's (2014) claim that Vernier learning with long-staircase training cannot transfer to a new location with same-location double training.

Hung and Seitz (2014) suggest that their method of using the first-staircase thresholds to estimate the learning and transfer effects is robust, in that "the qualitative pattern of results' statistical significance was resilient to other methods of threshold calculation" (p. 8424). In our data, the variations of the first-staircase thresholds are quite larger than those of the geometric means of five to six staircases in the pretraining and posttraining sessions. The first-staircase threshold calculation, thus, results in more variable estimations of the learning and transfer effects with smaller effect sizes (Figures 1 and 2).

On the other hand, whether and how much the fast and more variable learning effects from the first to second staircases of training can be treated as perceptual learning is uncertain. This fast learning effect may be disproportionately affected by procedural learning that most likely takes place in the early (fast) stage of learning (Fahle, Edelman, & Poggio, 1995; Karni & Sagi, 1993). When this fast learning effect dominates the performance changes (Figure 2), different treatments of this issue could lead to different research conclusions. The issue is not as severe when learning consists of both fast and more gradual learning as in the short-staircase training case (Figure 1).

Vernier learning with long-staircase training differs from that with short-staircase training in that no learning is evident after initial very fast learning (Figure 2). This observation is similar to previous reports that training with only hard trials prevents perceptual learning in most observers (Ahissar & Hochstein, 1997; Rubin, Nakayama, & Shapley, 1997). One difference is that, in these earlier studies, the performance is 50%–60% correct, but in our study, the staircase converges at a correct rate of 79.8%. However, such a higher correct rate is still near threshold and likely functions as "hard" trials. On the other hand, the insignificant learning effect with long-staircase training may be unrelated to the number of trials used. Censor and Sagi (2008) report that overtraining with a very large number of trials in a training session causes within-session perceptual deterioration and reduces between-session learning. As shown in Hung and Seitz (2014), even if the numbers of total trials are matched (~800 trials per session), short-staircase training produces significant learning, but long-staircase training produces weak and insignificant learning.

In this study, the experimental conditions are identical to those in our original study (Wang et al., 2014) except for the staircase length with long-staircase training. By doing so, we are able to examine whether Hung and Seitz's (2014) conclusions could apply to our own data. Although the stimulus conditions are largely similar to Hung and Seitz, there exists one noticeable difference. Hung and Seitz measure baseline Vernier thresholds for two orthogonal orientations at four retinal quadrants with one staircase each. In contrast, we only measure Vernier thresholds at two diagonal retinal quadrants. However, with more pretraining conditions, we would expect fewer fast learning effects but still unchanged thresholds afterward in our study. As a result, learning would become less significant regardless of whether the pretraining and posttraining thresholds are estimated with the first staircase values or with geometric means of all five to six staircases. When the learning effect is small, it is very difficult to decide whether and how much learning transfers to a new location.

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Acknowledgments

This research was supported by Natural Science Foundation of China Grants 31470975 (JYZ) and 31230030 (CY). We thank Dennis Levi, Stanley Klein, and Gong-Liang Zhang for helpful comments.

Commercial relationships: none.
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References

Ahissar, M., & Hochstein, S. (1997, May 22). Task difficulty and the specificity of perceptual learning. , *387*(6631), 401–406.

Bejjanki, V. R., Beck, J. M., Lu, Z. L., & Pouget, A. (2011). Perceptual learning as improved probabilistic inference in early sensory areas. , *14*(5), 642–648.

Censor, N., & Sagi, D. (2008). Benefits of efficient consolidation: Short training enables long-term resistance to perceptual adaptation induced by intensive testing. , *48*(7), 970–977.

Cumming, G. (2014). The new statistics: Why and how. , *25*(1), 7–29.

Dosher, B. A., & Lu, Z. L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. - *A* , *A*, *95*(23), 13988–13993.

Fahle, M., Edelman, S., & Poggio, T. (1995). Fast perceptual learning in hyperacuity. , *35*(21), 3003–3013.

Hung, S. C., & Seitz, A. R. (2014). Prolonged training at threshold promotes robust retinotopic specificity in perceptual learning. *J* , *34*(25), 8423–8431.

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *A* , *A*, *88*(11), 4966–4970.

Karni, A., & Sagi, D. (1993, September 16). The time course of learning a visual skill. , *365*(6443), 250–252.

Law, C. T., & Gold, J. I. (2009). Reinforcement learning can account for associative and perceptual learning on a visual-decision task. - , *12*(5), 655–663.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. , *10*(4), 437–442.

Poggio, T., Fahle, M., & Edelman, S. (1992, May 15). Fast perceptual learning in visual hyperacuity. , *256*(5059), 1018–1021.

Rubin, N., Nakayama, K., & Shapley, R. (1997). Abrupt learning and retinal size specificity in illusory-contour perception. *C* *B* , *7*(7), 461–467.

Schoups, A., Vogels, R., & Orban, G. A. (1995). Human perceptual learning in identifying the oblique orientation: Retinotopy, orientation specificity and monocularity. *J* , *483*(pt 3), 797–810.

Teich, A. F., & Qian, N. (2003). Learning and adaptation in a recurrent model of V1 orientation selectivity. *J* , *89*(4), 2086–2100.

Wang, R., Cong, L. J., & Yu, C. (2013). The classical TDT perceptual learning is mostly temporal learning. *J* , *13*(5):9, 1–9, https://doi.org/10.1167/16.5.9. [PubMed] [Article]

Wang, R., Zhang, J. Y., Klein, S. A., Levi, D. M., & Yu, C. (2012). Task relevancy and demand modulate double-training enabled transfer of perceptual learning. , *61*, 33–38.

Wang, R., Zhang, J. Y., Klein, S. A., Levi, D. M., &

Xiong, Y. Z., Zhang, J. Y., & Yu, C. (2016). Bottom-up and top-down influences at untrained conditions determine perceptual learning specificity and transfer. *E* , *5*, *14614*, 1–17.

Yu, C., Klein, S. A., & Levi, D. M. (2004). Perceptual learning in contrast discrimination and the (minimal) role of context. *J* , *4*(3):4, 169–182, https://doi.org/10.1167/4.3.4. [PubMed] [Article]

Zhang, J. Y., Wang, R., Klein, S. A., Levi, D. M., & Yu, C. (2011). Perceptual learning transfers to untrained retinal locations after double training: A piggyback effect. *J* , *11*(11):1026, https://doi.org/10.1167/11.11.1026. [Abstract]

Zhang, J. Y., & Yang, Y. X. (2014). Perception learning of motion direction discrimination transfers to an opposite direction with TPE training. , *99*, 93–98.

Zhang, J. Y., Zhang, G. L., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2010). Rule-based learning explains visual perceptual learning and its specificity and transfer. *J* , *30*(37), 12323–12328.